TURKISH REPUBLIC OF NORTHERN CYPRUS
NEAR EAST UNIVERSITY
INSTITUTE OF GRADUATE STUDIES

A three-dimensional finite element analysis of the effects of en-masse retraction on the anterior maxillary teeth with skeletal anchorage in lingual orthodontic treatment

MOHAMMAD GHANNAM
PhD THESIS

DEPARTMENT OF ORTHODONTICS

Assistant. Prof. Dr. Beste Kamiloğlu

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THESIS APPROVAL
Directorate of Institute of Health Sciences

This study was accepted by our jury as a doctoral thesis in the orthodontics program.

Head of Jury: Prof. Dr. Çağrı Ulusoy
Gazi Universitey. Orthodontics Department

Advisor: Assistant. Prof. Beste Kamiloğlu
Near East University. Orthodontics Department

Jury Member: Prof. Dr. Ulaş Öz
Near East University. Orthodontics Department

Jury Member: Associate. Prof. Dr. Çağrı Türköz
Gazi Universitey. Orthodontics Department

Jury Member: Associate. Prof. Dr. Levent Vahdettin
Near East University. Orthodontics Department

This thesis was approved by the above jury members in accordance with the relevant articles of the Near East University Graduate Education and Examination Regulations and accepted by the Board of Directors of the Institute.

Prof. Dr. Hüsnü Can Başer
Director of Institute of Health Sciences

STATEMENT (DECLARATION)

Hereby I declare that this thesis study is my own study, I had no unethical behavior in all stages from planning of the thesis until writing thereof, I obtained all the information in this thesis in academic and ethical rules, I provided reference to all of the information and comments which could not be obtained by this thesis study and took these references into the reference list and had no behavior of breeching patent rights and copyright infringement during the study and writing of this thesis.

Mohammad Ghannam

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LIST OF ABBREVIATIONS AND SYMBOLS

∘	Degree
٪	Percent
µm	Micrometer
Pa	Pascal
MPa	Mega pascal
GF	Gram-Force
GR	Grams
N	Newton
N/mm^2	Newtons per millimeter squared
mm	Millimeter
3D	Three dimensional
FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
CAD	Computer aided design
CT	Computed tomography
DICOM	Digital imaging and communications in medicine
PDL	Periodontal ligament

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Öğrenci Adı: Mohammad Ghannam
Danışman: Yard. Doç. Dr. Beste Kamiloğlu
Ortodonti Anabilim Dalı, Diş hekimliği Fakültesi, Yakın Doğu Üniversitesi

Özet

Amaç: Bu çalışmanın amacı, kaldıraç kolları farklı pozisyonlarda konumlandırıldığında ve kuvvet uygulama noktalarının farklı yüksekliklerde olduğu durumlarda, örneklerin ön maksiller dişlerinin total retraksiyonları sırasındaki başlangıç yer değiştirmelerini farklı yükseklikteki mini vidalar ile analiz etmek ve netleştirmektir.

Gereç ve Yöntem: Üç boyutlu (3D) sonlu eleman modelleri, mini vidanın farklı yükseklik ve pozisyonları ile kitlesel retraksiyonu uyarmak için oluşturuldu. Kuvvet uygulama noktalarını değiştirmek için Mini vidadan kaldıraç kollarına 150 g geri çekme kuvveti uygulanarak ilk diş yer değiştirmeleri analiz edildi.

Bulgular: Mini vida ve kaldıraç kolunun tüm yükseklik ve pozisyonlarında lingual kron devrilmesi ve oklüzal kron ekstrüzyonu görülmüştür. Ancak, örneklerdeki bu devrilme mini vida yüksekliği 8 mm olduğunda ve kaldıraç kolu lateral kesici dişler ile köpek dişleri arasına yerleştirildiği zaman daha az saptanmıştır.

Sonuç: Tüm mini vida yükseklikleri ve kaldıraç kolu pozisyonları; okluzal kron ekstrüzyonu, lingual kron devrilmesi ve labial kök devrilmesi göstermiştir. Bununla birlikte, 8 mm yüksekliğindeki bir mini vida ve kaldıraç kolunun yan kesici diş ve köpek dişi arasına yerleştirilmesi, köpek dişlerinin distaline yerleştirilen 4,5 mm yüksekliğindeki bir mini vida ve kaldıraç koluna kıyasla daha az miktarda devrilme göstermiştir. Bu nedenle, lingual teknik ile yapılan tedavide total retraksiyon sırasında ilave tork kontrol yöntemleri ile kuvvet uygulama noktası tercih edilebilir.

Anahtar Kelimeler: Diş Hareketi Teknikleri, Lingual Teknik Braketleri, Ortodontik Ankraj İşlemleri, Sonlu Elemanlar Analizi

Name of the student: Mohammad Ghannam
Name of the Supervisor: Assist. Prof. Dr. Beste Kamiloğlu
Department of Orthodontics, Faculty of Dentistry, Near East University

Abstract

Objective: This study aimed to analyze and clarify the initial displacement patterns of the anterior maxillary teeth during lingual en masse retraction with different miniscrew heights when the lever arms were located at different positions and the force application points were at different heights.

Materials and Methods: Three-dimensional (3D) finite element models were created to stimulate en masse retraction with different heights and positions of the miniscrew and lever arm to change the force application points; a 150-g retraction force was applied from the miniscrew to the lever arms, and the initial tooth displacements were analyzed.

Results: Lingual crown tipping and occlusal crown extrusion were seen at all heights and positions of the miniscrew and lever arm, but when the miniscrew height was at 8 mm and the lever arm was located between the lateral incisors and canines, these tipping patterns were less than those obtained with a 4.5-mm-high miniscrew and a lever arm located distal to the canines.

Conclusion: All miniscrew heights and lever arm positions showed initial lingual crown tipping and labial root tipping with occlusal crown extrusion. However, the 8-mm miniscrew height and the lever arm located between the lateral incisor and canine showed fewer amounts of these tipping patterns than a 4.5-mm miniscrew height and lever arm located distal to the canines. Therefore, this could be the preferred point of force application during en masse retraction in lingual treatment with additional torque control methods.

Keywords: Finite Element Analysis, Lingual Brackets, Orthodontic Anchorage Procedures, Tooth Movement Techniques

1- INTRODUCTION:

With the increasing adoption of orthodontic treatment among adult patients, especially female, patient esthetic demands have been reportedly increasing (Fillion, 1997). Lingual appliances address the esthetic requirements for such patients by attaching to the lingual surface of the teeth (Singh and Cox, 2011). There are many different aspects from labial orthodontic treatment in terms of application method, biomechanical properties and treatment course. The first generation of lingual orthodontic appliances was introduced by Kurz in the 1970s with his lingual edgewise appliance with an anterior bite plan and mesh pads to adapt to the tooth lingual surface and pre-torqued archwire (Kurz et al., 1982). Subsequently, Fujita introduced lingual mushroom-shaped wires that were developed to overcome the difference in labiolingual thickness between the anterior and posterior teeth (Fujita, 1979).

3D models extracted from cone-beam computed tomography (CBCT) scans of craniofacial structures including maxillary and mandibular dentitions made it possible to evaluate the treatment outcomes in all three planes of space (Leonardi et al., 2021). Leonardi et al. and Perillo et al. used 3D models derived from CBCT scans to evaluate skeletal changes or investigate craniofacial characteristics among different ethnic groups shows the accuracy and reliability of 3D techniques (Leonardi et al., 2021; Perillo et al., 2013).

To obtain successful outcomes in any orthodontic treatment, a good knowledge of biomechanics is mandatory, since the treatment's outcome primarily depends on the biomechanical principles applied during the treatment (Aravind et al., 2016). En masse retraction of the six maxillary anterior teeth as one unit to close an extraction space is a standard clinical practice procedure. To control the anchorage in the posterior teeth, miniscrews can be used to achieve maximal retraction of the anterior teeth during lingual orthodontic treatment (Feng et al., 2019). Variations in the direction of the applied retraction will result in multiple movement patterns of the anterior teeth, which may lead to unfavorable outcomes. Thus, it is crucial to understand the resultant effects of the different movement patterns during en masse retraction of the anterior maxillary teeth with the use of miniscrews in lingual orthodontics. A previous study investigated the movement tendencies of the maxillary anterior teeth during lingual en masse retraction with a single miniscrew height and two varied lever arm locations using the finite element method (Feng et al., 2019). Applying retraction force from different miniscrew heights could generate new movement patterns which could be favorable for function and esthetics. Three-dimensional finite element analysis can be used as an efficient computer simulation technique to imitate the orthodontic force application and analyze the resultant biomechanical actions of the teeth (Singh et al., 2016).

In light of this rationale, the miniscrew heights and lever arm locations and positions were varied to widen the possibility of determining favorable points of force application. A 3D finite element models with the alveolar bone, periodontal ligament, teeth, and lingual orthodontic system was constructed in the current study. The aim was to analyze the resultant displacement patterns after applying retraction force to identify the best line of action of force for functionally and esthetically pleased outcomes.

2- GENERAL INFORMATİON:

2.1. Development of Lingual Orthodontics

Studies on the lingual technique began in the 1970s. Miura et al. With the acid etching bonding system introduced in 1971, it was the first time that all orthodontic devices could be placed on the palatal or lingual surfaces of the teeth in a way that would not be visible from the outside (Miura et al., 1971).

Fujita began developing a custom lingual bracket system and presented several case reports in 1979 using this method (Fujita, 1979; Poon and Taverne, 1998). Kurz et al., In collaboration with Ormco Company, developed a special bracket for lingual applications, and in 1980 they tested these new brackets in approximately 80 patients (Kurz et al., 1982; Smith, 1983). In 1981, 6 leading American orthodontists formed a group called the "Lingual Task Force" to advance lingual orthodontics (Shum et al., 2004). Courses have been held worldwide, and many universities have included lingual orthodontics in their postgraduate orthodontics programs.

Fujita and Kurz developed bracket mechanics for use on lingual surfaces (Kurz et al., 1982; Fujita, 1979). Despite many publications on this subject, the lingual technique has received limited acceptance by orthodontists in many parts of the world (Kurz and Gorman, 1983; Alexander., et al 1983; Gorman et al., 1983; Scholz and Swartz 1982; Smith, 1983; Shum et al., 2004; Kelly, 1982; Artun, 1987; Creekmore, 1989; Smith et al., 1986; Romano, 1998; Kurz, 1989). This was due to the problems that emerged during the development of the lingual technique, the difficulty of application, and the increased chair time (Gorman et al., 1983; Smith et al., 1986; Fontenelle, 1991).

Technological advances in laboratory procedures and materials have brought many innovations to the lingual technique. (Wiechmann, 2001). Adult patients who need aesthetic treatment due to their social position have started to be more interested in the lingual technique. Since the patient's profile and lip position are not affected by brackets, it has been possible to preserve the aesthetic appearance and observes tooth position improvement during the treatment (Poon and Taverne, 1998; Garland-Parker, 1994).

Lingual brackets, preferred mostly by adult patients, have some advantages over labial devices:

1. The invisibility of lingual bracket meets patient esthetic demands

2. The teeth' labial surfaces are protected from the adverse effects of applications such as debonding and adhesive removal, from enamel decalcifications caused by plaques accumulating around the brackets.

3. Improvements in the positions of the teeth can be observed much more quickly.

4. Since lingual braces do not affect the lips' position, the effects on the treatment profile are better observed (Creekmore, 1989).

2.2. Biomechanical Differences Between Lingual and Labial Techniques:

2.2.1. Center of resistance, center of rotation and moment

The center of resistance is the point where the force vector that makes the tooth translation movement intersects the long axis of the tooth. It can also be defined as the 'balance point' (Tosun, 1999; Nanda and Kuhlberg, 1997). The shape of the movement that occurs when a force is applied to the tooth depends on the direction of the applied force and the distance of the application point to the center of resistance of the tooth. While a force or combination of forces passing through the center of resistance of the tooth makes a translation movement to the tooth, the forces passing away from it will create a moment and cause a tipping movement. The periodontal tissues surrounding them and the structures such as the alveolar bone in which they are located resist teeth' movement (Tosun, 1999, Burstone, 2000; Smith and Burstone 1984). The location of the center of resistance of a tooth; depends on root length, number and morphology, level of supporting alveolar bone. Therefore, its location is affected by periodontal disease, root resorption, and support bone loss (Nanda and Kuhlberg, 1997).

The center of rotation is the imaginary point around which the tooth makes a rotational movement due to the applied forces. The location of this point varies according to the forces applied to the tooth. As a result of a force applied to a single root tooth at the bracket level, a rotational center will form slightly apical to the center of resistance of the tooth, and the tooth will make a tipping movemet around this point. When the forces that make bodily translation movement are applied to the tooth, the center of rotation is located at infinity (Tosun, 1999; Burstone, 1966).

Forces whose line of action does not pass through the center of resistance of the tooth create a rotational effect around the center of rotation of the tooth. This effect is called the moment of force. The moment is the product of the intensity of the force and the vertical distance from the center of resistance of the tooth to this force's line of action and is expressed as "g-mm" in orthodontics literature (Smith and Burstone 1984).

In single root teeth, the center of resistance is located on the tooth's long axis at a distance of 24% - 35% of the root length from the alveolar crest (Tosun, 1999; Yoshida et al., 2001). The center of resistance of the upper molars is located approximately in the middle of the trifurcation in the vertical plane and closer to the palatal region in the horizontal plane. The center of resistance of the lower molars is located at the midpoint of the bifurcation in both vertical and horizontal planes (Scuzzo and Takemoto, 2003; Smith and Burstone 1984).

2.2.2. Biomechanical properties of lingual orthodontic treatment

When the relationship between the resistance center of the teeth and the force applied from the lingual side is evaluated, the biomechanics of tooth movement has different characters for lingual orthodontics than labial (Scuzzo and Takemoto, 2003; Sung et al., 2003; Geron et al., 2004). Scuzo and Takemoto summarized the effects of different orthodontic forces in three directions of space in the lingual and labial (Scuzzo and Takemoto, 2003).

When the relationship between the position of the lingual brackets placed on the upper incisors and the center of resistance of the tooth is examined, unlike the labial technique; The distance between the center of resistance and the lingual bracket slot is very close to each other (Geron et al., 2004) (Figure 2-1). Therefore, in the lingual technique, the effect of vertical forces on the incisor and canine teeth and the rotation effect of the force applied from the tooth's mesial and distal sides decreases (Scuzzo and Takemoto, 2003; Geron et al., 2004).

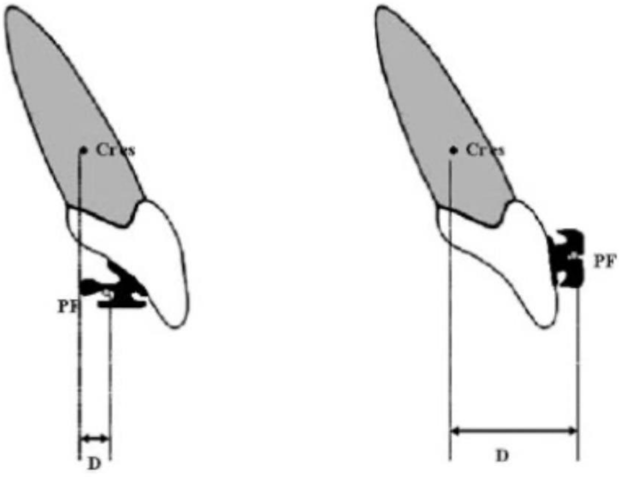


Figure 2-1: Relationship of lingual and labial brackets placed on the upper incisor with the center of resistance of the tooth (Geron et al., 2004).

Unlike the labial technique, since the lingual tube and/or brackets placed on the upper molar are located closer to the resistance centers of the teeth, the intrusion forces applied cause the crowns to tip more towards the lingual in the lingual technique and towards the buccal in the labial technique. On the other hand, since the center of resistance of the lower molars is located at the midpoint of the tooth, there are no significant differences between the moments created by the vertical forces applied by the lingual or labial attachments placed on it (Scuzzo and Takemoto, 2003).

Another difference is the contact point between the teeth. The contact points between the teeth in the molar region are closer to the buccal side. The wide interproximal gap formed on the lingual side causes the force applied from the lingual to rotate the crown more than the force applied from the labial when retraction forces are applied (Scuzzo and Takemoto, 2003).

2.2.2.1. Sagittal plane:

The net force vector that occurs when an equal amount of intrusion and retraction force is applied to the labial and lingual brackets placed on the incisors passes through the resistance center of the tooth in the labial system, and passes through the lingual side of the resistance center in the lingual system, creating a clockwise moment. Therefore, it creates a vertical bowing movement in the incisors. In lingual orthodontics, the amount of force should be decreased. The intrusion force should be increased during en-masse retraction to eliminate the side effects of retraction force (Scuzzo and Takemoto, 2003).

2.2.2.2. Vertical plane:

In lingual and labial techniques, the effect of intrusion forces applied to the upper incisors change depending on the axial inclination of the teeth. When a vertical orthodontic force is applied on an incisor with a normal axis inclination, depending on the force-resistance center relationship, the tooth rotates counterclockwise in labial and lingual techniques with the effect of the resulting moments. However, in the lingual technique, the amount of moment acting on the tooth is much smaller in proportion to the distance between the point of application of the force and the center of resistance (Scuzzo and Takemoto, 2003; Geron et al., 2004).

The intrusion forces applied from the labial and lingual surfaces on the upper incisor with increased axis inclination generates counterclockwise moments. However, in the labial technique, the amount of moment acting on the tooth is larger in proportion to the distance between the point of application of the force and the center of resistance (Scuzzo and Takemoto, 2003; Geron et al., 2004).

When an intrusion force is applied from the labial on an upper incisor with reduced axis inclination, a counterclockwise moment occurs, while when the lingual is applied, it creates a clockwise moment due to the position of the application point behind the center of resistance (Scuzzo and Takemoto, 2003; Geron et al., 2004).

A more effective intrusion is obtained with the vertical force applied from the lingual surface to a lower incisor with a normal axis inclination, depending on the relation of the lingual bracket slot to the center of resistance, than the force applied from the labial surface. Due to the moments that occur in the lingual technique, the amount of tipping of the crown towards the labial is less than the labial technique (Scuzzo and Takemoto, 2003).

2.2.2.3. Horizontal plane:

In the lingual technique, the distance between the brackets is less than in the labial technique (Figure 2-2). When a rotational movement is desired, the rotation moments created in the lingual technique are much less effective than in the labial technique. Due to the small distance between the brackets, more flexible archwire materials should be preferred, especially in crowding cases (Scuzzo and Takemoto, 2003; Geron et al., 2004; Moran, 1987].

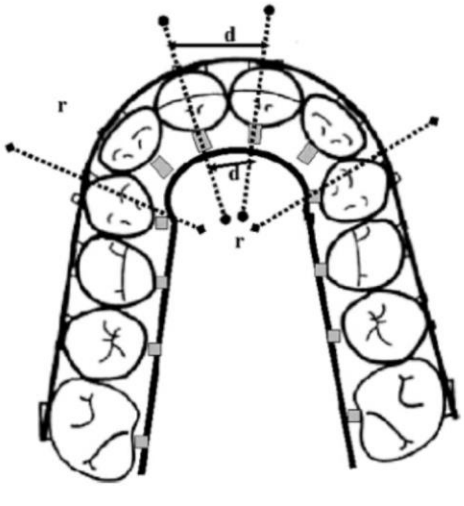


Figure 2-2: The distance between the brackets is shorter in the lingual technique than in the labial technique (Geron et al., 2004).

2.3. Closing extraction spaces and anchorage in orthodontics:

As a term, anchorage has been defined as "resistance to unwanted tooth movement" in orthodontic applications. The area where orthodontic strength is supported and has a high resistance to movement is the anchorage area. According to Newton's action-reaction law, the region is taken as an anchorage, and the force acting on the desired region of motion is opposite and equal to each other. Therefore, the resistances of these two regions determine the amount of movement of the regions towards each other (Zwemer, 1993; Moyers, 1958; Proffit, 2019).

Anchorage zone is defined as the area where orthodontic strength is supported, and resistance to movement is high. In orthodontics, the anchored areas can be briefly listed as a single tooth, group of teeth, entire arch, muscles, neck, skull, jaw tip, and skeletal system (Proffit, 2019; Graber and Vanarsdall, 2000).

Ricketts et al. Reported that cortical bone is more resistant to resorption and that the movement of the root within the cortical bone is slow. Especially in the lower jaw, which has a narrower bone structure, the anchorage of the posterior teeth can be strengthened by placing buccal root torque. This situation is defined as 'cortical bone anchorage' (Ricketts et al., 1978).

Closing extraction spaces takes place in various ways, following the philosophy of the technique in various treatment modalities. In standard Edgewise and segmented arch techniques, canines are retracted alone, or the incisors and canines are retracted together, depending on the needs of the case (Scuzzo and Takemoto, 2003; Nanda et al., 2005).

In frictional systems, canine retraction occurs as the tooth moves distally by sliding through arch wire. After the retraction of the canines is completed, the incisors are retracted by adding them to the anchorage of the posterior teeth (Nanda and Kuhlberg, 1997; Proffit, 2000; Nanda et al., 2005).

The retraction of incisors and canines as a group is called en masse retraction. In friction systems, the arch wire slides on the premolar and molar teeth. It is possible to obtain the protraction of the posterior teeth as well as the retraction of the anterior teeth [Scuzzo and Takemoto, 2003; Nanda and Kuhlberg, 1997; Burstone, 1995; McLaughlin et al., 2001).

2.3.1. Skeletal anchorage

In recent years, titanium screws have gained immense popularity in the orthodontic community and are considered absolute orthodontic anchorage sources (Park, 2001; Costa et al., 1998). The main advantages are easy insertion and removal, immediate loading, placement in various anatomical locations, including alveolar bone between tooth roots, and low cost (Lee et al., 2001).

Gainsforth and Higley proposed the skeletal anchorage idea in 1945, followed by the subsequent discoveration of osseointegration (Gainsforth and Higley, 1945). The concept of osseointegration was developed in 1969 by Brånemark et al. utilizing pure titanium implants (Brånemark et al., 1969). Kokich et al. used an ankylosed primary tooth to protract the maxilla to prove his modern absolute anchorage source in 1985 (Kokich et al., 1985). Furthermore, Umemori et al.' used the titanium mini-plate for intruding the lower posterior teeth (Umemori et al., 1999).

These screws have spawned a variety of dental uses, such as en mass retraction of anterior teeth. Buccal interdental gingival are places where mini-screws or tiny skeletal anchorages are placed (Park, 2001). The direction of placement of the mini-screw must also be addressed when selecting the correct length of the mini-screw. A mini-screw may be positioned either in a diagonal direction or in a perpendicular direction relative to the cortical bone surface (Paik et al., 2009). It is safer and simpler to position the mini-screws in a perpendicular direction. However, there are many cases in which the mini-screw can be positioned in a diagonal direction to prevent damage to the neighboring root of the tooth. When a mini-screw is inserted in a diagonal position rather than a perpendicular direction, it is best to use a longer mini-screws. Mini-screws constructed of titanium alloys of this thickness can be easily inserted without pre-drilling in maxillary buccal regions (Ludwig et al., 2008; Feldmann and Bondemark, 2006).

2.4. Extraction preferences

There are two main reasons for tooth extraction in orthodontics;

1. To create the space required to align the teeth in cases of severe crowding
2. Correcting the dental relationship and creating the ideal overjet-overbite relationship in cases of CI II, CIII or Bimaxillary protrusion (Proffit, 2019; Graber and Vanarsdall, 2000).

The most common extraction pattern; is the extraction of the first and second premolars. While the amount and region of crowding affect the alternatives, intermaxillary dental relations and facial aesthetics determine the extraction indications. For example; While four first premolar extraction are performed in Class I bidentoalveolar maxillary protrusion cases, in Class II maxillary protrusion cases, only the upper first premolar extraction is considered, in order to ensure the Class I relationship, lower second premolar extraction is among the alternatives, in Class III cases the lower first premolar extraction helps to correct the negative overjet (Proffit, 2019; Nanda et al., 2005).

Due to biomechanical differences, extraction options in lingual orthodontics may differ according to the labial technique. The mesial movement of the lower molars is difficult, especially due to the strong molar anchorage formed in the lower arc. In lingual orthodontics, the lower molar leveling stage makes the tipping movement towards the distal. This movement of the molars carries the Class I relationship to the Class II. Therefore, in Class I cases, the upper first premolar and lower second premolar extraction gives better results than four premolar extraction. In Class II cases, extraction in the lower arch should be avoided as much as possible. If the amount of crowding is mild, a solution with protrusion or stripping should be preferred. If the lower anterior crowding is severe, incisor extraction can be considered. In Class III cases, premolar extraction facilitates the lingual tipping of the lower incisors. The distal tipping movement of the lower molar formed in the leveling stage helps to correct the Class III molar relationship (Scuzzo and Takemoto, 2003; Takemoto, 1995).

There are two main advantages of extractions in the lingual technique:

1. Stronger anchorage: The mechanical advantage of the lingual treatment is buccal root torque and distal rotation in posterior teeth. Previously, Ricketts et al. identified it as a cortical bone anchorage, which increases the amount of anchorage in the lingual technique, while the anchorage in the lower dental arch is more than the upper dental arch. Therefore, lower second premolar extraction is more preferred in lingual cases (Ricketts et al., 1978).
2. Resolving deep bites: In Ormco 7th generation lingual brackets, intrusion movement is observed in the incisors due to the bite plane in the upper incisor brackets. The opening of the bite mostly takes place by the intrusion of the lower and upper incisors and some molar extrusion.

Fundamental problems encountered in cases with extractions in lingual treatments;

- Vertical and Horizontal bowing effects.
- The difficulty of coordinating upper and lower arch forms.
- Periodontal health problems, mostly seen in adult patients (Scuzzo and Takemoto, 2003; Takemoto, 1995).

2.5. En masse retraction in orthodontics

In orthodontic treatment, retracting the anterior six teeth as a single unit is defined as en masse retraction. It was first applied with Begg and Tip-Edge edgewise brackets for many years (Begg and Kesling, 1977; Kesling, 1992). In the modern edgewise technique, Andrews first presented the en-masse retraction method he used. Later, Bennett and McLaughlin developed Andrews' retraction method, and it has been used routinely in their own "Preadjusted Appliance System" (Andrews, 1976; McLaughlin and Bennett, 1989; Bennett and McLaughlin, 1990). Burstone improved the segmental T loop mechanics and argued that it was more effective in en masse retraction (Burstone, 1966).

There are two en-masse retraction mechanics; sliding mechanics (frictionally) and loop mechanics (frictionless) (Nanda and Kuhlberg, 1997).

In friction (sliding) mechanics; The retraction movement is achieved by the movement of the brackets along the wire or the sliding of the archwire between the brackets and tubes. Friction plays a vital role in the movement along the archwire, which is why it is called frictional mechanics (Nanda and Kuhlberg, 1997).

Frictionless (segmental) mechanics were developed by Charles J. Burstone et al. at Connecticut University. The basic principle of the technique is to hold the anterior and posterior segments together and treat them like a single massive tooth. Each segment is fixed within itself by placing thick wires before closing the spaces and retracted with T loop arcs. According to Burstone, with these mechanics, since the applied forces and moments can be determined in advance, tooth movements are more controlled, and at the same time, forces of constant and optimal intensity can be applied (Burstone, 1966, Burstone, 1995).

Heo et al. Did not find a significant difference between the two methods in their study in which they evaluated cases with incisor retraction in the upper jaw with en-masse retraction and canine retraction followed by subsequent incisor retraction in terms of anchorage loss (Heo et al., 2007).

Yoshida et al. compared the fourth incisors retraction and the en masse retraction of the anterior six teeth in the upper jaw and the centers of resistance of teeth in each method. They found that the center of resistance that occurred in the en masse retraction was located more incisal than the center of resistance to the incisor retraction (Yoshida et al., 2001).

Studies on en-masse retraction have recently focused on anchorage reinforcement methods. Erverdi et al. stated that Zygomatic bone anchorage is recommended to reinforce anchorage during en-masse retraction in Class II div I patients treated with a labial technique (Erverdi and Acar, 2005). Chung et al. stated that en masse retraction would be more successful by increasing the posterior anchorage using micro-implants in bi-dentoalveolar protrusion cases (Chung et al., 2007).

According to Scuzzo and Takemoto; Due to the high aesthetic expectations in lingual patients, the gaps formed in the anterior region with canine retraction create problems in appearance. In lingual orthodontics, retraction of canines separately as in labial orthodontics causes many aesthetic and mechanical problems. Retraction of a complete canine shortens the bracket distance between the canine and the premolar and the amount of activation applied in sliding or loop mechanics due to the inset bend located in the distal of the canine. For these reasons, en masse retraction is the most preferred method to close the extraction spaces in lingual orthodontics (Scuzzo and Takemoto, 2003).

2.5.1 En masse retraction with skeletal anchorage

In premolar extraction situations, the regulation of force vectors and moments is critical if the maxillary anterior Teeth are retracted. The moment to force ratio added on the upper fore teeth defines the movement of the tooth, such as uncontrolled tipping, controlled tipping, bodily or root movement. In addition, the direction and application point of the retraction force in relation to the location of the resistance center (CR) are crucial considerations for detecting and preparing the esthetic movement of the anterior teeth. The direction of application of force was mostly regulated by adjusting the vertical force vector, which is affected by the duration and location of the retracting hooks on the working wires and the mini implants' position. In forecasting and planning orthodontic tooth movement, both the biomechanical rules identified with the tooth resistance center and the archwire deformation can be considered. However, this regulation has been found complicated by anatomical limitations and specific patient differences (Tominaga et al., 2009).

Besides, it is assumed that the appliance's combination with the correct location of the mini-screw would enable the bodily movement and the efficiency of the anterior teeth to be retracted. As a result, the direction of forces coming from temporary anchoring devices and the length of the lever arm in en-mass retraction has the effect of producing a pattern of maxillary displacements of the anterior teeth, such as body movement or tipping.

2.6. Orthodontic tooth movement and optimum forces

Tooth movement is the biological response that occurs as a result of orthodontic forces. Mechanical stimulation created by the orthodontic force on the teeth triggers physiological activity that causes resorption and apposition in the bone, and tooth movement occurs. The force system acting on the tooth creates tension in the periodontium. This stretch causes tension or compression in cells, fibrils, and other tissues in the periodontal ligament. The biological response depends on the character of the stress-strain in the periodontium (Nanda, 1997; Proffit, 2019).

The factors that initiate tooth movement are the tension and deformations in the periodontal ligament. Therefore, the surface area of the periodontal ligament and root morphology affect the resulting stresses. It has been reported that stronger forces applied for orthodontic tooth movement carry a greater risk of root resorption (Faltin et al., 2001). The use of force at optimum intensity is also of great importance in this respect.

Optimum force is the amount of force that creates maximum tooth movement without tissue damage and without affecting patient comfort (Proffit, 2019). In the past, many researchers reported that the optimum amount of force was proportional to the root surface area of the tooth (Proffit, 2019; Moyers, 1958). In the 1950s and 1960s, some researchers, especially Begg, argued that the optimum forces are light (Storey and Smith, 1952; Begg, 1956). Many investigators report optimum force values for different tooth movements based on clinical experience and animal or human experiments (Faltin et al., 2001; Storey and Smith, 1952; McLaughlin and Bennett 1989; Berman, 1988). In their work based on the "pressure hypothesis" proposed by Smith and Storey, Lee, suggested the average pressure that provides optimum tooth movement is 197 gf cm2 (Storey and Smith, 1952; Lee, 1996). Based on the same study, Ricketts et al. reported the optimum pressure for tooth movement as 200 gf cm2, cm2 100 gf for bioprogressive treatment mechanics (Ricketts et al., 1978).

Today, the optimum amount of force required for the desired tooth movements has not yet been determined. Ren et al. Reported that it is almost impossible to measure the stress values in the periodontal ligament in practice and therefore concluded that it is difficult to experimentally determine the threshold value or optimum force for tooth movement (Ren et al., 2003).

The ideal approach to determining optimum forces; is measuring the force generated by the appliances and their evaluation according to individual and specific treatment goals. Force magnitudes for some appliance designs have been reported previously. However, the ideal force levels required for different types of tooth movements are still not fully known. However, knowing the amount of force the appliances apply to the teeth helps determine the optimum forces (Ren et al., 2004).

2.7. Stress-strain analysis methods

Many analysis methods examine the effects of orthodontic forces on teeth and supporting tissues. These;

1. Photo-elastic method.
2. Strain gauge.
3. Stress analysis with a laser beam (holographic interferometry).
4. Finite Element Analysis (Geramy, 2002).

1- Photo-elastic stress analysis:

Photo-elasticity stress analysis is based on the properties of some transparent materials that exhibit colored properties when examined under polarized light. This method is used to observe the flow of force in non-geometric bodies. In the model of the object to be examined, prepared from photoelasticity material, the stress regions are determined by the polariscope device. This method requires a well-equipped laboratory, specially prepared models, and a unique measurement instrument (Tanne et al., 1987; Mahler and Peyton, 1955).

2- Strain Gauge:

Strain gauges are devices used to detect linear shape changes occurring in structures under load. It is based on the principle that the electrical resistance of the conductor changes when it is subjected to mechanical deformation. It provides results related to strain under static and dynamic loads in vivo or in vitro conditions. In this method, strain sensitive tips are placed on the areas to be examined. This method examines dimensional changes under stress with calibrated electrical resistance elements (Caputo and Standlee, 1987).

3- Stress analysis with a laser beam (Holographic interferometer):

A hologram is a process of recording the microscopic interference fringes created by the mutual effect of two rays emanating from a coherent light source, which is used to obtain a 3-dimensional image of objects. In holography, interference and diffraction phenomena, which are the two basic light properties, are used. In this method, an instrument called interferometry is used that remotely measures light interference fringes. It measures the amount of spacing and displacement on objects with two laser beams it extracts. When the object is moved during the irradiation; The conclusion is reached by evaluating the eaves shaped in the holographic image (Burstone and Pryputniewicz, 1980).

4- Finite Element Analysis:

Finite element analysis is a numerical stress analysis technique applied to structures with irregular geometry showing many different material properties and can measure the stresses and displacements in detail. It needs detailed mathematical modeling and an excellent analysis program (Geramy, 2002).

2.8. Finite element analysis

Finite element analysis; It is a powerful computer simulation method that solves the stress-strain problems of structures in engineering. Briefly, it is defined as "a method of analysis based on obtaining realistic results by dividing complex systems into logical numbers of elements" (Hughes, 1987; Moaveni, 2003).

Finite element analysis was first used in the aircraft industry in 1956. It is a frequently used analysis method in many engineering departments, such as construction and mechanical engineering. With this method, numerical problems in which parameters such as area problems, stress, strain, displacement, and temperature distribution are investigated and defined by differential or integral equations can be solved with an acceptable approximation. Although finite element analysis was originally developed to calculate stresses in complex aircraft structures, it was later used in many fields such as heat transfer, fluid mechanics, acoustics, electromagnetism, and biomechanics (Hughes, 1987; Moaveni, 2003).

The first study on finite element analysis in dentistry was the research conducted by Ledley and Huang in 1968. In this study, forces were applied in various directions to a tooth whose mathematical model was created. The stresses caused by these forces in the bone tissue supporting the tooth were evaluated (Ledley and Huang, 1968).

The use of this method in orthodontics started in 1971 with the dental model that Davidian made to find the theoretical center of rotation of the upper central incisor. In this study, the mechanical response in the periodontium resulting from the force applied to the tooth was examined, and rotation and the displacement of the center of resistance were observed (Davidian, 1971). Since then, finite element analysis has been widely used to examine the stresses occurring in many structures such as teeth, periodontal membrane, alveolar bone, dental implants (Tanne et al., 1987).

2.8.1. Advantages and disadvantages of finite element analysis method

Advantages of the finite element analysis method:

- Can be used in many fields such as heat transfer, magnetic field, stress analysis,
- The ability to prepare a model that is very close to the real structure by applying to solids that do not show proper geometry and structures with different material properties,
- Versatility and flexibility in complex structures, giving more sensitive results than analytical and experimental methods,
- The ability to model objects made up of various layers to reflect the physical properties of layers and the combined properties between layers,

- The adhesion, friction, and contacts between different surfaces can be created close to reality,
- Accurate calculation of stress, strain, and displacements,
- The ability to change the properties such as geometry, boundary conditions, loading direction, the number of the created model, and the ability to repeat the analysis if required,
- It allows the simulation of designs that cannot be tested as prototypes or dangerous designs (Hughes, 1987; Moaveni, 2003).
- Despite all these advantages, finite element analysis is a simulation created by researchers. Therefore, it is the responsibility of the researcher to provide features such as material properties, which are very important in the accuracy of the simulation, the installation of the system, the need for knowledge of computer hardware, and the capacity of the finite element package program to apply real conditions on the solid model (Holmgren et al., 1998).

The resultant stress and displacements are initial that occur only at the first moment (Tanne et al., 1987). Depending on the time and the change of the system, the characteristics of the movement that will occur later may change, time-dependent studies are carried out to predict the changes, and the analysis should be supported with algorithms created according to the model (Schneider et al., 2002).

2.8.2. Finite element analysis working system

The stages of finite element analysis,

- Identifying and Modeling the problem,
- Creating a network structure by dividing the model into a finite number of elements and nodes,
- Defining boundary conditions and physical properties,
- Defining the coordinate system,
- Formulation of the problem,

- Obtaining algebraic equations and solving these equations,
- Interpretation of the results (Hughes, 1987; Moaveni, 2003).

The first step in finite element analysis is to recognize the structure and all properties of the problem to be studied. Thus, the model representing the problem and the possibilities to be solved are determined (Hughes, 1987; Moaveni, 2003).

The accuracy of the geometric model created is one of the most important factors determining the accuracy of the analysis results (Hughes, 1987; Moaveni, 2003). The transferring of the three-dimensional models to a computer environment can be obtained by,

a) Transferring MR and CT images to a computer program,
b) The object to be modeled can be scanned with scanners and then transferred to a computer program,
c) Drawing the models by the researcher using three-dimensional modeling programs (Chen et al., 2006).

The geometric model of the object to be analyzed is transformed into a mesh structure in a computer environment. This structure is called a mathematical model. The mathematical model consists of a finite (definite) number of elements, mostly at their junction with each other, with a certain number of nodes (nodes) where geometry and freedom are defined. These elements, which emerge by dividing the main model into different geometries, fully show the model's original features. It is essential to use as many elements as possible to measure the force distribution precisely. The physical behavior of the system is determined by the geometries and material properties of the finite elements. For this purpose, the Poisson Ratio and the elasticity modulus (Young's Modulus) values, which determine the material properties, are introduced into the computer program. According to a specific starting point, the coordinates of all nodes on x, y, and z axes are determined and transferred to the computer. Boundary conditions of the object are determined; identify where the model is fixed and where the force is applied. In the created mathematical model, matrices are formed for the changes that occur by applying the simplest external factors and boundary conditions to the nodes. These matrices are solved with the computer's help. In this way, the stress, strain, and displacements in each element and thus in the whole body formed by the elements are obtained (Hughes, 1987; Moaveni, 2003).

Today, models consisting of thousands of elements are used in finite element analysis. This means that thousands of stress, strain, and displacement values are obtained in direct proportion to the number of nodes for each model. To understand and interpret many data obtained, the displacement and stress values of the nodes at critical points, animations of the entire model, and images with color scales taken from different angles are used. The numerical values revealed by tables or graphs give the stress values caused by the displacements in three directions of space at the critical points and the forces applied to the model. In images with color scales, it is possible to see the entire model's stress distribution and displacements from different angles. The range of values that the colors correspond to is shown with a scale in the images. In enlarged images and animations, displacements with very small values are enlarged equally and become easier to understand.

2.8.3. Concepts related to finite element analysis

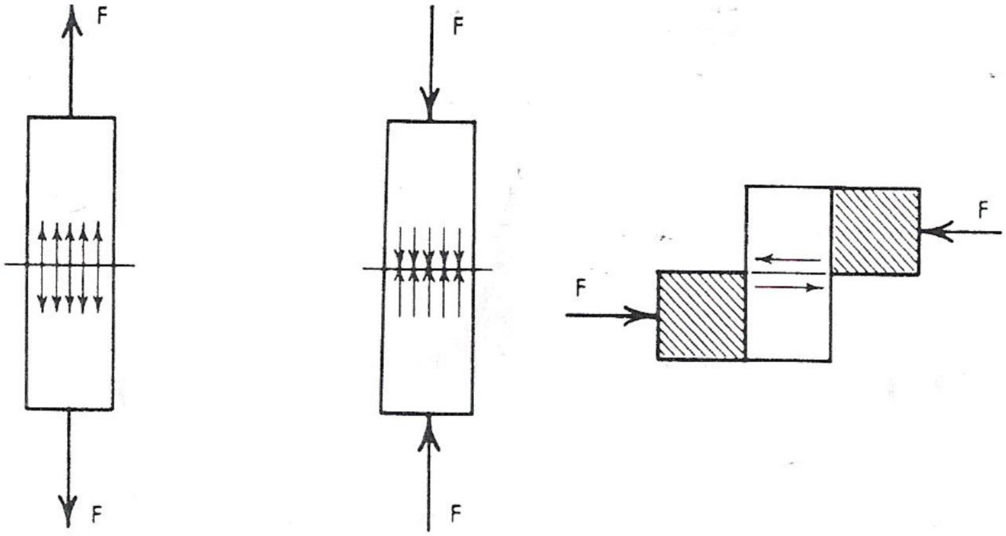
2.8.3.1. Force

The effect that can change the motion and shape of objects is called force. Force is a vector quantity and has vector properties such as direction, duration, and intensity (Burstone, 2000; Moaveni, 2003; Ledley and Huang, 1968). The force unit is "newton" (N) in the SI system, and N = kg. It is formulated as m / s2. The force of 1 Newton is the application of a 1 kg mass at 1 m / second2. In orthodontics literature, the quantities of forces are given in terms of "gram-force" (GF), but they are generally used as "grams" (GR), resembling the unit of mass. One newton is equal to 101.97 gram-force (Kuhlberg and Nanda, 2005).

2.8.3.2. Stress

Stress can be defined as the reaction in a unit area against a force applied to an object. Both applied force and internal stress dissipate over the entire surface of the body. Stress inside a structure is called the force per unit area. It is formulated as Stress = Force / Area. Generally, Pascal term (1Pa = 1N / m2 = 1MN / mm2) is used as the unit of stress (Franklin, 1998). However, in dentistry fields, Mega pascal (Mpa or N / mm2) is generally preferred (1MPa = 106 Pa) because the dimensions examined are millimetric.

Forces applied from different angles, or directions can often create complex stresses in the structure. The components of these forces determine the type of stress. Those in the direction perpendicular to the field create perpendicular (normal) stress components. Those tangents to the field create shear stress components. Three basic types of stress occur (Craig and Powers, 2002) (Figure 2.4).



a) Tensile Stress b) Compressive Stress c) Shear stress

Figure 2-4: Stress types

Tensile stress: It is the type of stress that forces the molecules of the object to separate from each other and occurs when two forces in the same direction but in the opposite direction affect the object (Figure 2.4-a).

Compressive stress: It occurs when two forces in the same direction and in the opposite direction affect the object, forcing the molecules of the object to approach each other (Figure 2.4-b).

Shear stress: It occurs when two forces at different levels and opposite directions that force the molecules of the object to slide parallel to the surface on each other simultaneously affect the object (Figure 2.4-c).

2.8.3.3. Principle stress

The stresses in which the shear stresses in all planes are zero, and all the stresses consist only of normal stresses perpendicular to the area are called principal stresses. Prime stress; maximum principal stress, intermediate principal stress, and minimum principal stress. However, instead of a single type of stress, a combined stress state in which three types of stresses come together occurs in the bodies where loads are applied. (Franklin, 1998; Marghitu, 2001).

The distribution of compressive and tensile stresses is examined according to the principal stress distribution. The maximum principal stresses are positive and represent the highest tensile stresses (tensile stress). Minimum principal stresses are negative values and represent the highest compressive stresses. In the data obtained from the analysis results, positive values represent stresses in the form of tensile, and negative values denote stresses in compression. Whichever strain pattern has the greater absolute value at a node, the effect of that strain is evident. (Sung et al., 2003).

2.8.3.4. Von misses stress

Von Mises stress is used to determine the stress criteria in ductile materials. Combining the principal stresses that occur in two or three dimensions, it gives the tensile strength of the material loaded in one direction. Von Mises stresses are also used to measure fracture toughness. Stress is generally expressed in three dimensions. Von Mises stresses transform the three-dimensional expression into a single positive number that can be read on a scale to evaluate the strain criteria. (Cattaneo et al., 2003; Gallas et al., 2005).

2.8.3.5. Strain

Strain is the dimensional deformation that occurs per unit size when a certain force is applied to an object. While the force applied to the object creates tension, it also creates strain (Franklin, 1998). Strain does not have a unit of measure. However, strain can be defined as the ratio of deformation to the original length (Craig and Powers, 2002).

Strain = Change in size / Original size.

Objects can change dimensionally in two different ways when force is applied. In elastic deformation, the object can return to its original size after the force is removed. In plastic deformation, the object cannot return to its initial dimension after the force is removed. If the stress exceeds the resultant force per unit area, ruptures and fractures occur in the body (Graber and Vanarsdall, 2000).

2.8.3.6. Elasticity limit

It is the maximum stress that the object can withstand against a certain force without plastic deformation. It can also be defined as the maximum load-extension limit at which the object exhibits elasticity (Nanda et al., 2005).

2.8.3.7. Elastic modulus (Young's Modulus)

The modulus of elasticity is a coefficient indicating the strength of the body within its elasticity limits, i.e., the Stress / Strain ratio (Nanda, 1997). Elasticity module takes different values for different materials. As this value increases, the resistance of the object against elongation will increase. More rigid materials have higher internal resistance and, thus, elastic modulus (Craig and Powers, 2002). This property is in an indirect relationship with its mechanical properties. Linear (linear) elasticity materials have a constant young modulus, whereas non-linear elasticity materials show variability depending on the applied load (Yoshida et al., 2001; Shaw et al., 2004).

2.8.3.8. Poisson’s ratio

The ratio of the unit size change in the width of the objects within the elasticity limit to the unit size change in the length under tensile or compression forces. For example, when pulling force acts on an object, there is a lengthening in the direction of the load and a lengthening in other dimensions perpendicular to the load. Under compression forces, the length of the object gets shorter, and its width thickens (Franklin, 1998).

2.8.3.9. Isotropic body

The isotropic body shows the same elastic properties in different directions. Thus, the stress-strain relationships can be expressed depending on two material constants (elasticity modulus and Poisson ratio) (Hughes, 1987; Moaveni, 2003).

2.8.3.10. Homogeneous body

Objects in which elastic properties are the same at every point in the object are named as homogeneous objects (Franklin, 1998).

2.8.3.11. Element

To perform finite element analysis; The geometric model created is divided into simple geometric shapes called "elements". Elements are classified according to their geometry (triangle, parallelogram, quadrilateral), dimensions (one-dimensional, two-dimensional, rotary elements, three-dimensional elements), number of nodes, unknowns in the number of nodes and characteristics of the continuous environment problem (solid, shell, beam) (Hughes, 1987; Moaveni, 2003).

2.8.3.12. Rigid element

Rigid elements are elements that transmit force but do not undergo deformation and are not stressed. They are used to keep the distance between the connected nodes constant (Hughes, 1987; Moaveni, 2003).

2.8.3.13. Dimensional beam element (3D Beam Element)

The 3D beam element is a general-purpose finite element type and can perform 3-dimensional operations. These elements can transmit force and moment in 3 directions (x y z), and materials can be assigned to these elements. The element is described by two nodes in space. A third node is used to describe the element coordinate system without having a degree of freedom. There are 12 degrees of freedom for two nodes fixing both ends of the element. Each node has three translational and three rotational freedoms. The element can resist force in any direction and rotational force around any axis (Hughes, 1987; Moaveni, 2003; Franklin, 1998; Marghitu, 2001).

2.8.3.14. Node

In finite element analysis, the model behavior is divided into several previously determined elements. Elements are recombined at points called "nodes". In this way, an algebraic set of equations is obtained. In stress analysis, these equations are equilibrium equations at nodes. Depending on the problem under investigation, hundreds or even thousands of equations are obtained in this way. The solution of this set of equations requires the use of computers (Hughes, 1987; Moaveni, 2003; Franklin, 1998; Marghitu, 2001).

2.8.3.15. Creating a network structure (Mesh)

The process of creating a mesh structure creates the coordinates of nodes and elements. Simultaneously, it automatically sorts and enumerates nodes and elements in optimum time against the minimum information entered by the user. In producing meshes, the user may also need to decide which regions will have higher element density and which regions will have less element density in the area on which the mesh will be produced. Generally, more elements are placed per unit area in regions known to be significant or have a large gradient (change) in themselves or can be predicted. In creating meshes, models are divided into a finite number of elements. These elements are connected to each other at specific points; these points are called nodes. For example, the displacements of each element in solid models are directly related to the displacements at the nodal points. Displacements at the node points are related to the stresses of the elements. It tries to solve the displacements in these nodes by creating a mesh (Hughes, 1987; Moaveni, 2003; Franklin, 1998; Marghitu, 2001).

2.8.3.16. Boundary conditions

Boundary conditions include boundary expressions of stresses and displacements. It shows the points where the object is fixed, and the force is applied. The boundary conditions of the analyzed object are determined according to the application points and conditions of the force (Hughes, 1987; Moaveni, 2003; Franklin, 1998; Marghitu, 2001).

Boundary condition is critical to the accuracy of an FE model. It consists of restrictions in the interfaces. In sliding mechanics, wires can slip in the bracket slots. The archwire acts as a guide. The teeth slide on the wire through the brackets to control the end position by the wire. There is a gap between the bracket slot and the wire. When a force is applied to a tooth, it is the first displacement of the tooth. Due to the low elastic behavior of the PDL, the crown tends to have a relatively large displacement, which changes the contact state of the wire and bracket. The sliding between the wire and the bracket, the interaction between the wire and the bracket, and the contact between the root and the bone affect the load on the tooth and trigger the tooth movement. Therefore, the ability to model the load system more realistically is needed for sliding mechanics, including bone, PDL, thread, elbow, and wire.

2.8.4. Finite element analysis studies in orthodontics

Sung et al. Compared the effectiveness of compensation curves applied during lower canine distalization in lingual and labial techniques and found that the efficiency of compensation curves increased as the amount of bending increased, and the same amount of bendings applied was more effective in the labial technique (Sung et al., 2003).

Chang et al. compared the en-masse retraction results using a multi-loop edgewise arc with a straight ideal archwire in the upper second molar extraction case. The multi-loop edgewise arc has been advantageous in terms of force distribution and movement due to the application of the CI II elastic force (Chang et al., 2004).

Wang et al. In his study, the mesial movements of the upper first molar at different types of force loading in lingual and labial techniques were compared comparatively. In the mesial force application, the upper first molar tipped to the mesial, rotated distolingually in the lingual technique, while in the labial technique, it tipped mesially and rotated distobuccally. The amount of tipping and rotation in the labial technique is more than the lingual technique. When it is desired to significantly move to the first molars, the amount of movement in the lingual technique is more than the labial technique. The lingual technique is more effective when the mass movement of the upper first molars is desired in the mesial direction (Wang et al., 2008).

Using the finite element process, McGuinness et al. (1992) assessed the spread of orthodontic forces delivered by the Edgewise unit. An upper canine bracket with a 0.022-in slot and a wire filling the slot was subjected to a force of 98.1 g. The forces were applied from the front to the back, parallel to the orthodontic wire. The authors discovered that the PDL's cervical margin and the tooth apex were the areas with the most tension accumulation (McGuinness et al., 1992).

3- MATERIAL AND METHODS

Three-dimensional geometric models with finite element analysis that contained the first premolar extraction space and lingual system were used. To establish the 3D finite element models with the maxilla and the maxillary dentition, computed tomography scans of an adult male's dry skull were acquired from the Visible Human Project® (US National Library of Medicine, Bethesda, MD). The scans were then modified into a meshwork using the VRMesh Design (Virtual Grid Inc, Bellevue City, WA) software. The periodontal ligament structure was formed evenly with 0.25-mm thickness (Geramy et al., 2014). Around the PDL and on all outer bone surfaces, the cortical bone was formed evenly with 1-mm thickness, and the cancellous bone filled the remaining bone areas (Farnsworth et al., 2011).

Next, 0.018 × 0.025-inch slot ORMCO 7th generation lingual brackets, 0.016 × 0.022-inch stainless steel ORMCO (Ormco, Glendora, CA) preformed mushroom-shaped lingual archwires, and lever arms and miniscrews (Ormco VectorTAS orthodontic implant; length of the miniscrew, 10.7 mm) were modeled with the Rhinoceros 4.0 (McNeel & Associates, Seattle, WA) software using the original shapes and dimensions. The lever arm varied between two locations with three different heights from the archwire plane: 6 mm, 8 mm, and 10 mm. The first location was mesial to the canine in the midpoint between the lateral incisor and canine. The second location was distal to the canine. The lever arms were extended toward the gingiva and palatal mucosa. The miniscrews were located between the first and second maxillary molars at two different heights from the archwire plane, 4.5 mm and 8 mm (Park et al., 2019). The maxillary first premolars were removed to accommodate the en masse retraction.

Twelve models were formed according to varied locations and heights of lever arms and miniscrews and transferred into ALGOR FEMPRO software (ALGOR, Inc. Pittsburgh, PA) to generate the finite element analysis (Figure 3-1; 3-2). In all models, the structure of teeth, periodontal ligament, cortical and cancellous bone, brackets, and archwire was formed using 8-node brick elements.

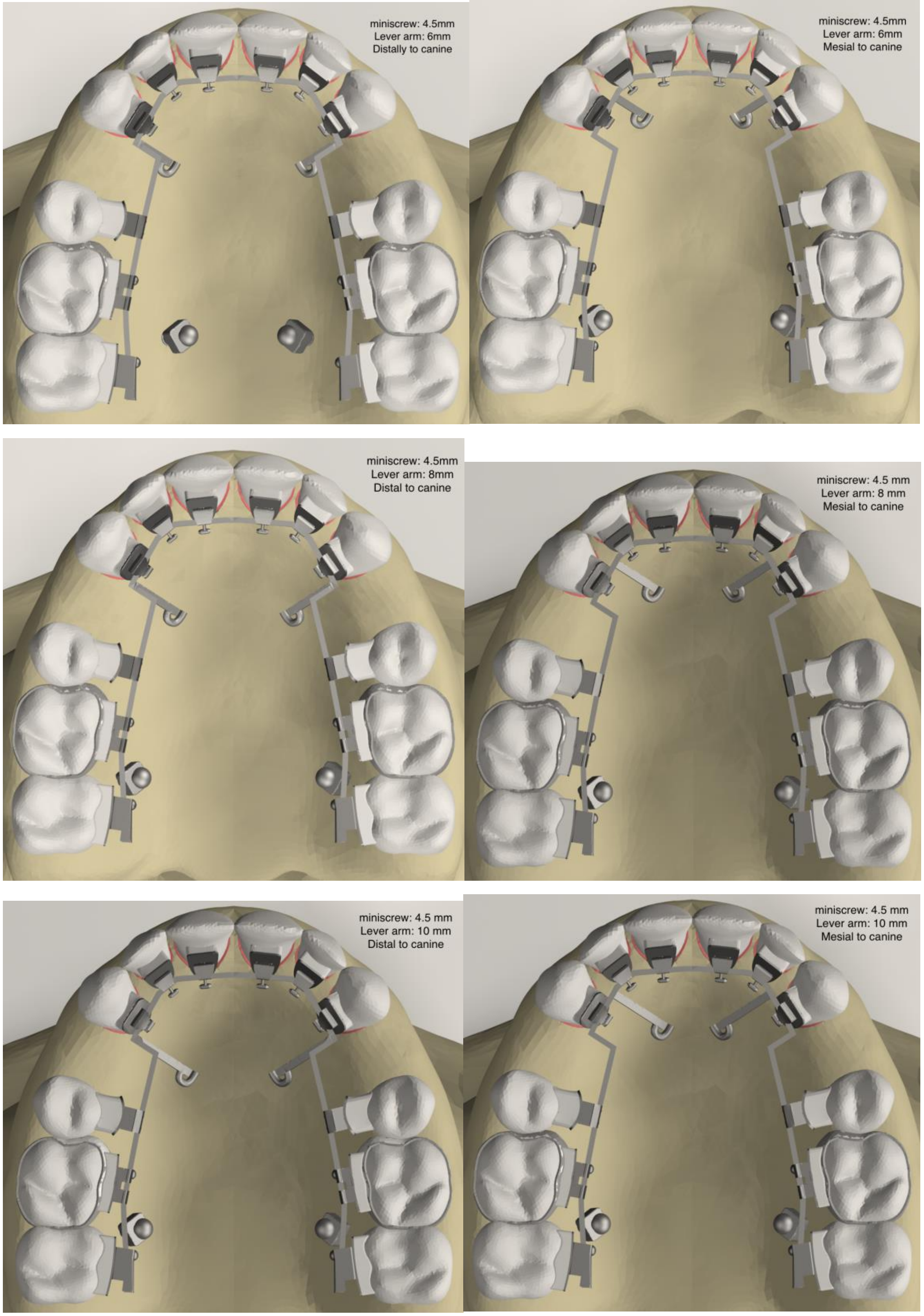


Figure 3-1 The 4.5 mm miniscrew height with distally and mesially to the canine lever arms.

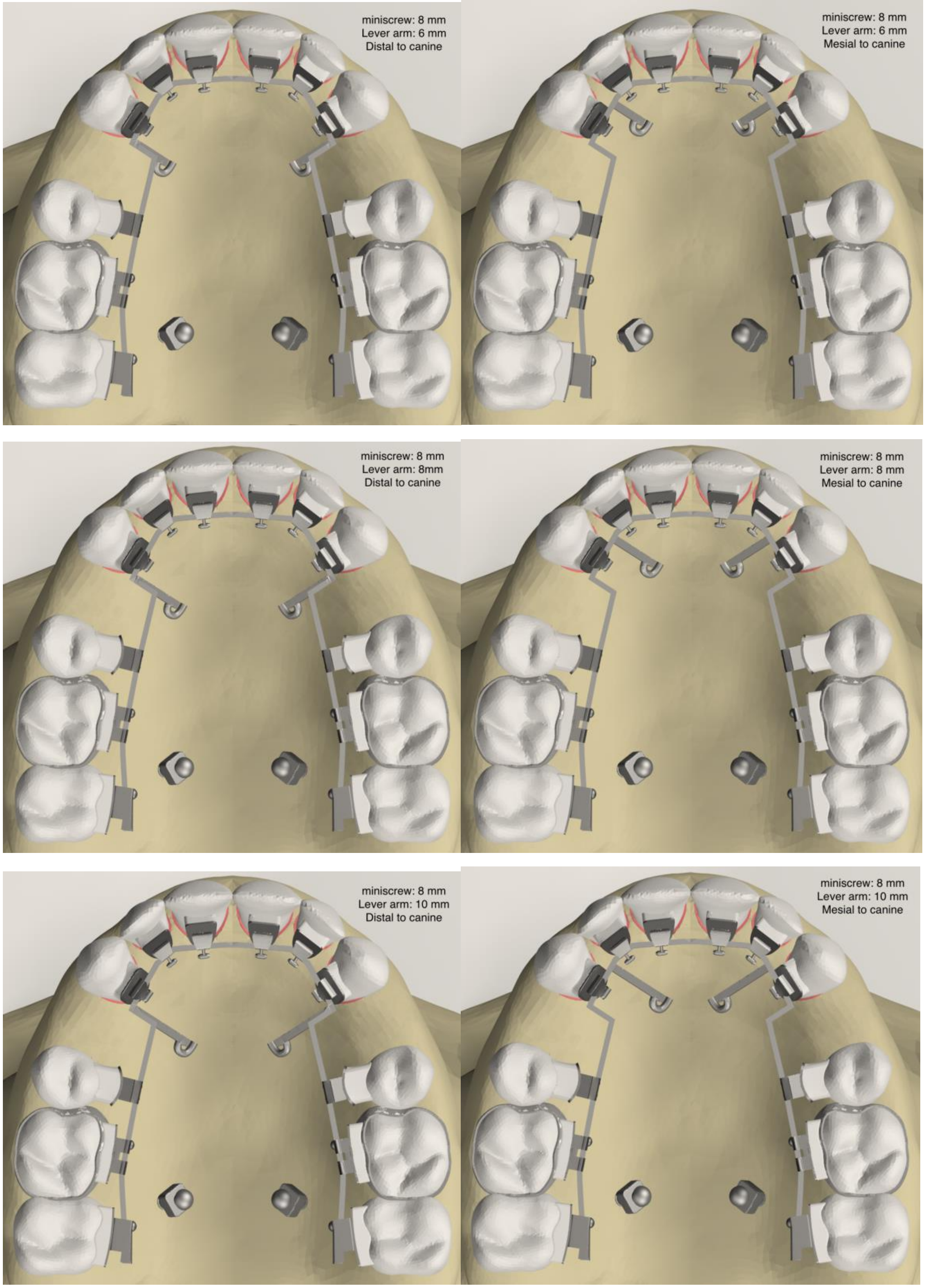
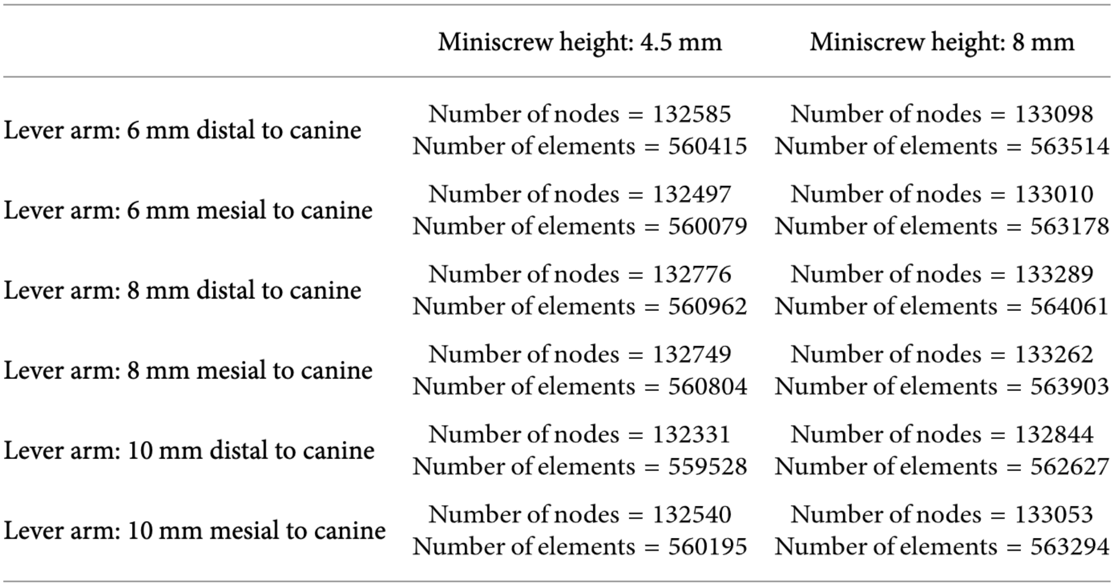


Figure 3-2 The 8 mm miniscrew height with distally and mesially to the canine lever arms.

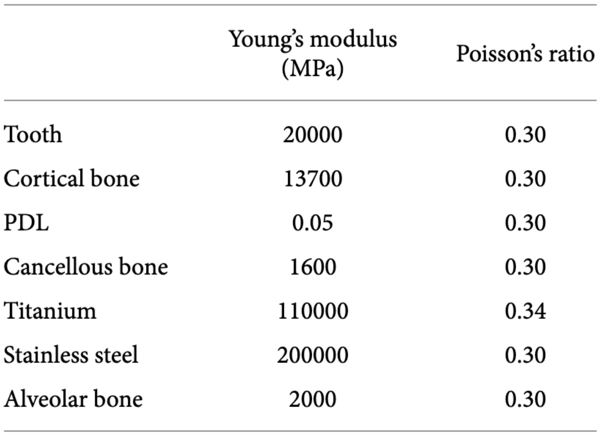
In areas close to the center of the structures in the models, 6-node wedge, 5-node pyramid, and 4-node tetrahedral elements were also used. Table 3-1 shows the number of nodes and elements used for each model.



	Miniscrew height: 4.5 mm	Miniscrew height: 8 mm
Lever arm: 6 mm distal to canine	Number of nodes = 132585 Number of elements = 560415	Number of nodes = 133098 Number of elements = 563514
Lever arm: 6 mm mesial to canine	Number of nodes = 132497 Number of elements = 560079	Number of nodes = 133010 Number of elements = 563178
Lever arm: 8 mm distal to canine	Number of nodes = 132776 Number of elements = 560962	Number of nodes = 133289 Number of elements = 564061
Lever arm: 8 mm mesial to canine	Number of nodes = 132749 Number of elements = 560804	Number of nodes = 133262 Number of elements = 563903
Lever arm: 10 mm distal to canine	Number of nodes = 132331 Number of elements = 559528	Number of nodes = 132844 Number of elements = 562627
Lever arm: 10 mm mesial to canine	Number of nodes = 132540 Number of elements = 560195	Number of nodes = 133053 Number of elements = 563294

Table 3-1 Number of nodes and elements for each model.

All structures in the models were determined as linear elastic, homogeneous, and isotropic (Nihara et al., 2015]. Table 3-2 shows the material properties that were used (Jasmine et al., 2012).



	Young's modulus (MPa)	Poisson's ratio
Tooth	20000	0.30
Cortical bone	13700	0.30
PDL	0.05	0.30
Cancellous bone	1600	0.30
Titanium	110000	0.34
Stainless steel	200000	0.30
Alveolar bone	2000	0.30

Table 3-2 Material properties of the models.

The boundary conditions were determined in the areas where the maxillary bone ends. The archwire was not allowed to move in a palatal direction, preventing it from moving out of the bracket.

The force application points were at a vertical distance of 6, 8, and 10 mm from the archwire plane on the lever arm, and a 150-g retraction force was applied from the miniscrew to the identified point on the lever arm. In order to analyze the initial displacement patterns, a 3D coordinate system was used. The coordinate system incorporated the X, Y, and Z axes perpendicular to each other. The X-axis indicated labio-lingual displacements: + lingual, - labial; the Y-axis indicated the mesiodistal direction: + mesial, - distal; and the Z-axis indicated the vertical direction: + occlusal, - apical. Reference points were placed on the incisal edges of crowns (Figure 3-4) and root apices (Figure 3-5) in order to measure tooth displacement. The resultant initial displacement of these nodes on the X, Y, and Z axes after force application was analyzed.

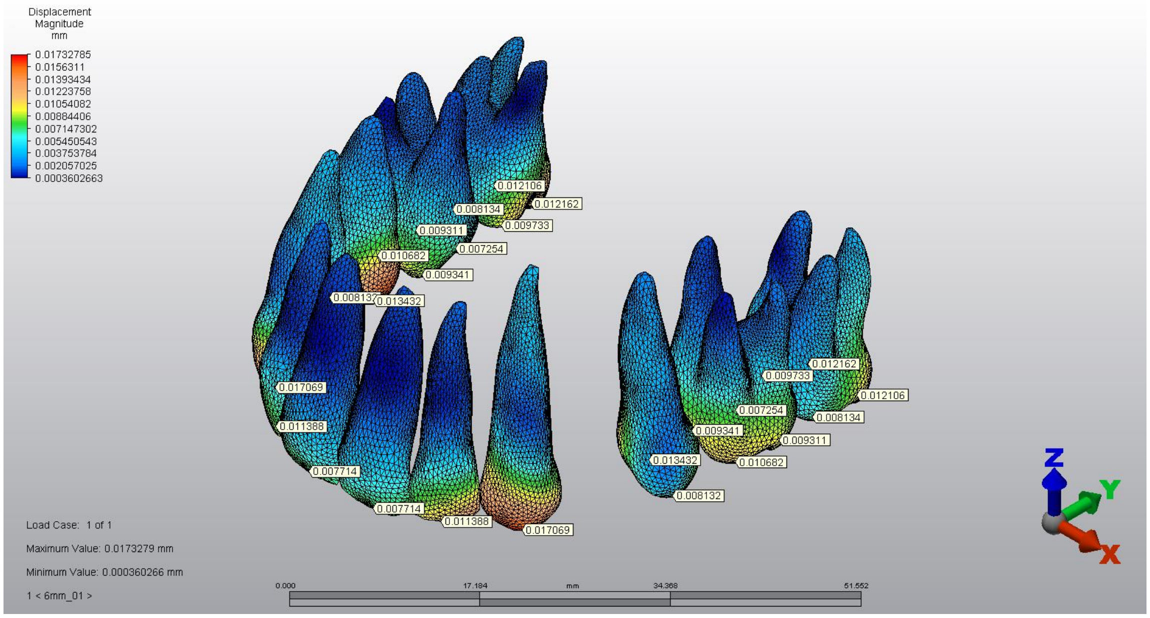


Figure 3-4 Example of Measurements of the reference points on the incisal edges of the crowns.

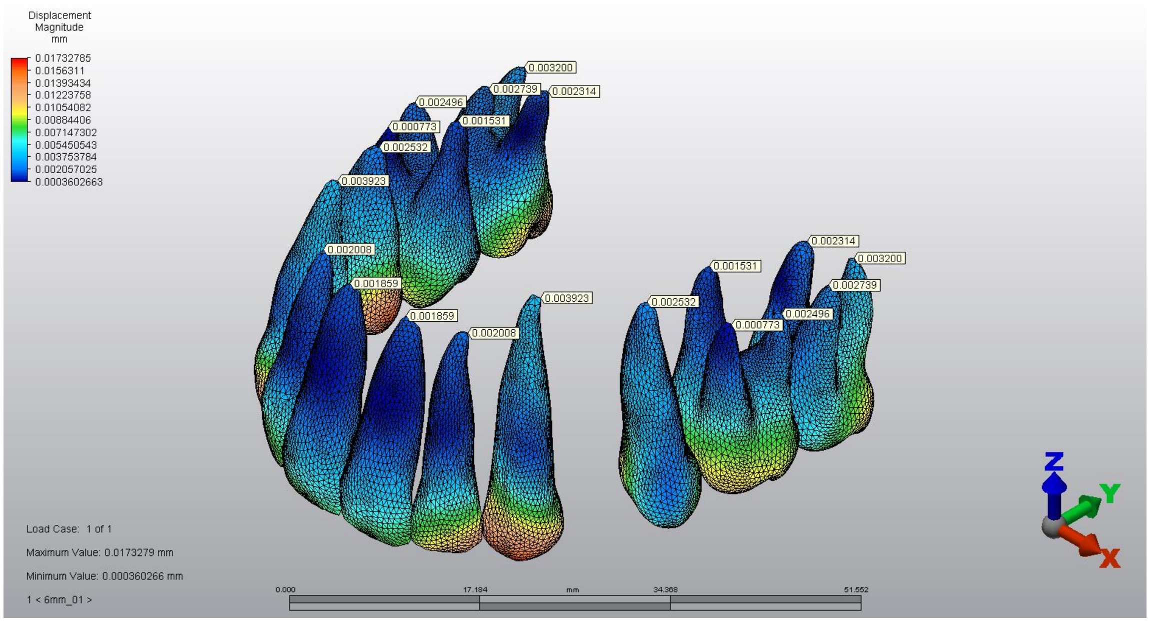
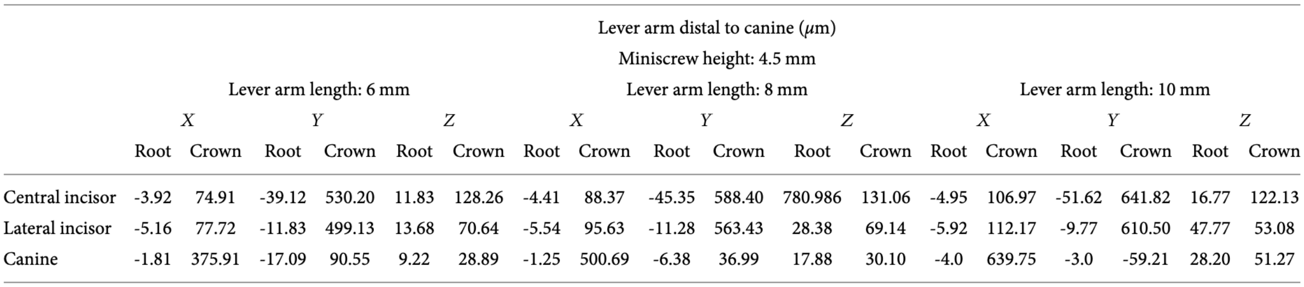


Figure 3-5 Example of Measurements of the reference points on the root apices.

4- RESULTS

After applying retraction force with the lever arm located distal to the canine with the miniscrew height at 4.5 mm and lever arm 6 mm (C6-4.5), the maxillary incisors and canines showed lingual crown tipping and labial root tipping, mesial crown tipping and distal root tipping with crown and root occlusal extrusion. (Table 4-1). With the lever arm length increased to 8 mm (C8-4.5), the maxillary incisors and canines still showed lingual crown tipping and labial root tipping, mesial crown tipping and distal root tipping with crown and root occlusal extrusion. (Table 4-1). Finally, at a lever arm length of 10 mm (C10-4.5), the maxillary incisors and canines again showed lingual crown tipping and significantly increased labial root tipping. The maxillary incisors showed mesial crown tipping and distal root tipping, while the canines showed both crown and root distal tipping. The maxillary incisors and canines showed both crown and root occlusal extrusion (Table 4-1).



	Lever arm distal to canine (μm) Miniscrew height: 4.5 mm																	
	Lever arm length: 6 mm						Lever arm length: 8 mm						Lever arm length: 10 mm					
	X		*Y*		*Z*		*X*		*Y*		*Z*		*X*		*Y*		*Z*	
	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown
Central incisor	-3.92	74.91	-39.12	530.20	11.83	128.26	-4.41	88.37	-45.35	588.40	780.986	131.06	-4.95	106.97	-51.62	641.82	16.77	122.13
Lateral incisor	-5.16	77.72	-11.83	499.13	13.68	70.64	-5.54	95.63	-11.28	563.43	28.38	69.14	-5.92	112.17	-9.77	610.50	47.77	53.08
Canine	-1.81	375.91	-17.09	90.55	9.22	28.89	-1.25	500.69	-6.38	36.99	17.88	30.10	-4.0	639.75	-3.0	-59.21	28.20	51.27

Table 4-1 Initial tooth displacements following the application of retraction force (X: + lingual, - labial; Y: + mesial, - distal; Z: + occlusal, - apical).

In the corresponding measurements performed with the lever arm located distal to the canine with the miniscrew height at 8 mm and lever arm length 6 mm (C6-8), the maxillary incisors and canines showed lingual crown tipping and labial root tipping, less mesial crown tipping and more distal root tipping when compared to C6-4.5. Both crown and root occlusal extrusion was also present (Table 4-2). With lever arm length 8 mm (C8-8), after application of the retraction force, the maxillary incisors and canines again showed lingual crown tipping and labial root tipping. The maxillary incisors showed mesial crown tipping and distal root tipping, while the canines showed both crown and root distal tipping. In all teeth both crown and root occlusal extrusion was also seen (Table 4-2). Finally, with lever arm length 10 mm (C10-8), the maxillary incisors and canines showed lingual crown tipping and labial root tipping. The maxillary incisors showed also mesial crown tipping and distal root tipping, while the canines also showed both crown and root distal tipping. Both crown and root occlusal extrusion were also present (Table 4-2).

	Lever arm distal to canine (μm)																	
	Miniscrew height: 8 mm																	
	Lever arm length: 6 mm						Lever arm length: 8 mm						Lever arm length: 10 mm					
	X		*Y*		*Z*		*X*		*Y*		*Z*		*X*		*Y*		*Z*	
	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown
Central incisor	-3.25	73.21	-52.35	530.01	10.47	107.97	-3.96	93.43	-60.62	608.97	26.95	107.54	-4.80	116.88	-68.30	667.58	46.70	81.83
Lateral incisor	-4.68	66.51	-24.30	474.38	33.73	51.82	-5.71	83.95	-18.62	543.86	51.37	40.80	-6.10	107.68	-21.84	602.97	74.54	24.11
Canine	-5.48	446.97	-23.62	26.45	2.36	45.92	-5.06	638.91	-11.98	-83.46	9.86	88.15	-7.06	752.63	-9.44	-151.54	22.69	82.41

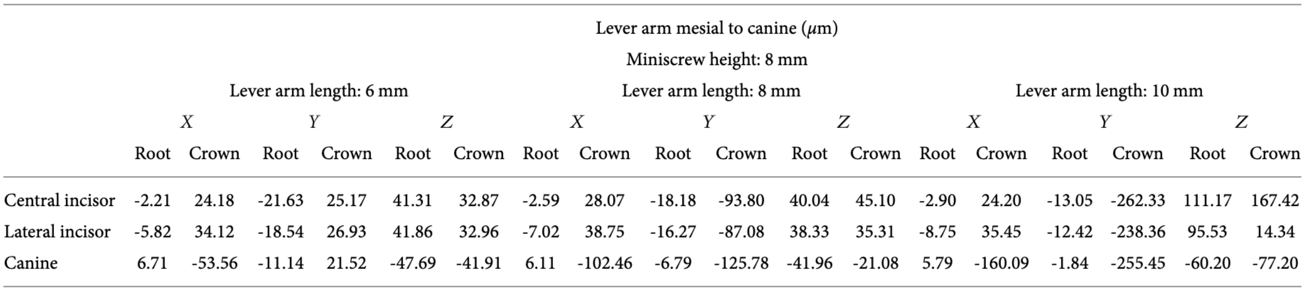
Table 4-2 Initial tooth displacements following the application of retraction force (X: + lingual, - labial; Y: + mesial, - distal; Z: + occlusal, - apical).

In another set of measurements obtained after application of the retraction force with the lever arm located between the lateral incisor and canine with a miniscrew height of 4.5 mm and lever arm length 6 mm (C6-4.5), the maxillary incisors showed lingual crown tipping and labial root tipping, while the canines showed labial crown tipping and lingual root tipping. The maxillary incisors and canines showed mesial crown tipping and distal root tipping. The maxillary incisors also showed both crown and root occlusal extrusion, while the canines showed both crown and root intrusion (Table 4-3). At C8-4.5, the maxillary incisors again showed lingual crown tipping and labial root tipping while the canines also showed labial crown tipping and lingual root tipping. The maxillary central incisors showed both crown and root distal tipping, while the lateral incisors and canines showed mesial crown tipping and distal root tipping. The maxillary incisors showed both crown and root occlusal extrusion, while the canines showed both crown and root apical intrusion (Table 4-3). Finally, at C10-4.5, the maxillary incisors still showed lingual crown tipping and labial root tipping and the canines showed labial crown tipping and lingual root tipping. The maxillary incisors showed both crown and root distal tipping, while the canines showed crown distal tipping and distal root tipping. The maxillary incisors showed both crown and root occlusal extrusion, while the canines showed both crown and root apical intrusion (Table 4-3).

	Lever arm mesial to canine (μm)																	
	Miniscrew height: 4.5 mm																	
	Lever arm length: 6 mm						Lever arm length: 8 mm						Lever arm length: 10 mm					
	X		*Y*		*Z*		*X*		*Y*		*Z*		*X*		*Y*		*Z*	
	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown
Central incisor	-2.66	21.19	-12.20	74.07	13.77	3.88	-2.97	23.42	-9.35	-26.77	71.95	90.17	-3.12	20.53	-5.11	-189.63	80.13	123.65
Lateral incisor	-5.71	44.54	-8.23	104.58	17.36	7.0	-6.68	46.38	-7.14	5.55	65.36	80.25	-7.99	43.20	-4.96	-146.69	70.42	101.86
Canine	10.84	-116.20	-8.65	124.93	-36.70	-5.16	9.45	-149.42	-3.73	26.89	-53.41	-65.62	8.77	-200.47	1.76	-106.26	-51.29	-44.27

Table 4-3 Initial tooth displacements following the application of retraction force (X: + lingual, - labial; Y: + mesial, - distal; Z: + occlusal, - apical).

In the next set of measurements obtained after application of a retraction force with the lever arm located between the lateral incisor and canine, at C6-8, the maxillary incisors showed lingual crown tipping and labial root tipping while the canines showed labial crown tipping and lingual root tipping. The maxillary incisors and canines showed mesial crown tipping and distal root tipping. The maxillary incisors showed both crown and root occlusal extrusion, while the canines showed both crown and root apical intrusion (Table 4-4). At C8-8, the maxillary incisors again showed lingual crown tipping and labial root tipping and the canines showed labial crown tipping and lingual root tipping. The maxillary incisors showed mesial crown tipping and distal root tipping, while the canines showed both crown and root distal displacement. The maxillary incisors again showed both crown and root occlusal extrusion, and the canines showed both crown and root apical intrusion (Table 4-4). Finally, at C10-8, the maxillary incisors again showed lingual crown tipping and labial root tipping and the canines showed labial crown tipping and lingual root tipping. Similar to C8-8, the maxillary incisors showed mesial crown tipping and distal root tipping and the canines showed both crown and root distal displacement. The maxillary incisors showed both crown and occlusal extrusion, while the canines showed apical crown and root intrusion (Table 4-4).



	Lever arm mesial to canine (μm)																	
	Miniscrew height: 8 mm																	
	Lever arm length: 6 mm						Lever arm length: 8 mm						Lever arm length: 10 mm					
	X		*Y*		*Z*		*X*		*Y*		*Z*		*X*		*Y*		*Z*	
	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown	Root	Crown
Central incisor	-2.21	24.18	-21.63	25.17	41.31	32.87	-2.59	28.07	-18.18	-93.80	40.04	45.10	-2.90	24.20	-13.05	-262.33	111.17	167.42
Lateral incisor	-5.82	34.12	-18.54	26.93	41.86	32.96	-7.02	38.75	-16.27	-87.08	38.33	35.31	-8.75	35.45	-12.42	-238.36	95.53	14.34
Canine	6.71	-53.56	-11.14	21.52	-47.69	-41.91	6.11	-102.46	-6.79	-125.78	-41.96	-21.08	5.79	-160.09	-1.84	-255.45	-60.20	-77.20

Table 4-4 Initial tooth displacements following the application of retraction force (X: + lingual, - labial; Y: + mesial, - distal; Z: + occlusal, - apical).

5- DISCUSSION

This study aimed to identify the best locations of force application points during lingual en masse retraction of the anterior maxillary teeth by varying the vertical distances of both the miniscrew and power arm and their locations. The findings of the current study showed that all points of force application used generated lingual tipping with extrusion of the anterior maxillary teeth. However, the 8 mm miniscrew height with the power arm located between the lateral incisor and canine resulted in the least amount of these patterns.

In lingual en masse retraction, the six anterior teeth are retracted as one unit because the lingual archwires have mushroom-shaped curves at the distal side of the canines (Kim et al., 2011). Moreover, any space between the anterior teeth is not considered esthetic in lingual orthodontics (Lombardo et al., 2014). With utilizing the biomechanical considerations of lingual appliances, skeletal malocclusions and craniofacial appearances can be treated and enhanced (Yanagita et al., 2014).

During closure of extraction spaces in lingual orthodontics, loss of torque control of the anterior teeth occurs, causing a vertical bowing effect that includes lingual tipping of the maxillary incisors (Lawson, 2013). Liang et al. performed a 3D finite element study to compare lingual and labial orthodontics and found that under the same loading, the maxillary incisors showed lingual crown tipping in lingual orthodontics while bodily translation occurred in labial orthodontics (Liang et al., 2009). Mascarenhas et al. in their finite element study stated that the amount of lingual forces as compared to labial forces were quantified and found to be 32,8 % lesser in lingual orthodontics (Mascarenhas et al., 2015). Furthermore, in a systemic review by Ata-Ali et al., treatment with lingual appliances tended to tip incisors by generating a lingual crown torque (Ata-Ali et al., 2017).

Feng et al. conducted a 3D finite element study comparing two different lever arm locations with a single miniscrew position and concluded that lever arms located between the lateral incisor and canine can yield better anterior tooth torque control than lever arms located distal to the canine but still cannot achieve reasonable torque of the anterior maxillary teeth without additional torque control methods (Feng et al., 2019). In agreement with our findings, when the lever arm location was distal to the canine, the maxillary incisors and canines showed lingual crown tipping and labial root tipping, which increased as the length of the lever arm increased from 6 mm to 10 mm, with no difference between the 4.5- and 8-mm miniscrew heights.

Nevertheless, when the lever arm location was between the lateral incisor and canine, the maxillary incisors showed less lingual crown and labial root tipping than those seen with the lever arm located distal to the canine, and these tipping patterns were lesser when the miniscrew height was 8 mm than at 4.5 mm. However, the maxillary canines showed labial crown tipping and lingual root tipping, which was also lesser when the miniscrew height was 8 mm. This may be attributed to the transverse bowing effect of the lingual retraction force on the archwire (Lombardo et al., 2014).

A study by Stamm et al. showed that 10° of torque changes caused a 1.2-mm vertical change in the anterior maxillary teeth, thus affecting the esthetics of the anterior teeth (Stamm et al., 2000). In our study, the occlusal crown extrusion of the maxillary incisors was less when the miniscrew height was at 8 mm and the lever arm was located between the lateral incisor and canine and increased as the length of the lever arm increased, while the canines showed apical and crown intrusion. Thus, variations of the anterior tooth torque caused changes in vertical distance. This was also seen when the lever arm location was distal to the canines with both miniscrew heights, indicating that good torque control of the anterior teeth helps vertical control of the anterior teeth to gain esthetically acceptable results.

Because of the small inter-bracket distance in lingual appliances, archwires greater than 016 X 022-inch stainless steel cannot be installed into an 0.018-inch slot (Romano, 2006). This results in 14° of play between the archwire and bracket slot (Sebanc et al., 1984). Therefore, torque loss is inevitable. Normally teeth will tip until the archwire contacts the diagonal corners of the bracket slot. This shows the limitation of finite element method as it only allows us to analyze initial displacements. As the teeth move under the impact of the forces, changes in movement patterns cannot be anticipated (Chacko et al., 2018). This might explain the recurrence of the resultant tipping patterns despite the varied points of force application in the current study.

In vitro experiments by Lossdörfer et al. and Daratsianos et al., the torque control capability of fully customized lingual appliances was studied. These studies revealed that better torque control could be accomplished due to high precision of the bracket slot archwire companion in fully customized lingual appliances (Lossdörfer et al., 2014; Daratsianos et al., 2016).

Chacko et al. in their finite element study used frictionless (loops) mechanics to retract the anterior teeth with lingual appliances. They found that good torque control was attainable using T loop with 30° gable bends as the loop delivered lower forces and higher moment to force ratios (Chacko et al., 2018).

Anchorage control is essential for successful orthodontic treatment because loss of anchorage can yield poor treatment outcomes. Miniscrews in lingual orthodontics can preserve anchorage and ultimately lead to good treatment outcomes (Geron, 2006). By combining miniscrews and lingual power arms in the retraction system, different movement patterns can be obtained with different lengths and different positions of the power arms and miniscrews (Hong et al., 2005).

The posterior palate is considered a suitable location for miniscrew insertion (Kravitz et al., 2007). Specifically, the palatal alveolus between the first and second molars offers a large interradicular space and wide cortical plate (Ludwig et al., 2011; King et al., 2007). However, injury to the greater palatine artery is a risk factor associated with insertion of a miniscrew in that area. Tavelli et al. identified the safety zone between the cementoenamel junction of the maxillary molars and the greater palatine artery to be 13.9 ± 1 mm (Tavelli et al., 2019). In our 3D models, the miniscrews were placed at 4.5 mm and 8 mm from the archwire plane, which was approximately 4 and 6 mm, respectively, from the cementoenamel junction within the identified safety zone.

Finally, our study was limited in that it investigated initial displacements only. Long term orthodontic movement might not be the same as the initial movement. Especially when many teeth are connected with an archwire, the force system varies with tooth movement. Although this study considered initial displacements with different retraction force directions rather than continuous, it provided some guidance for clinical treatment planning in lingual orthodontics and characterized the versatility of the 3D finite element method.

6- CONCLUSION

It can be concluded that despite the limitation mentioned in this study, placing the lever arm between lateral incisor and canine with miniscrew height 8-mm could be the preferred line of action of retraction force with additional torque control methods during en masse retraction in lingual treatment. However, these results are right only for the initial movement, which is produced by elastic deformation of the PDL.

Future continuous displacement finite element analysis studies and studies in a clinical setting are recommended to verify the results of this study.

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CURRICULUM VITAE

Name	Mohammad	**Surname**	Ghannam
Place of Birth	Saudi Arabia	**Date of Birth**	17/03/1991
Nationality	Syrian	**Tel**	
E-mail	muh.ghannam@gmail.com		

Educational Level

	Name of the Institution where he/she was graduated	Graduation year
Postgraduate/Specialization	PhD in Orthodontics	2021
Masters	-	-
Undergraduate	Doctor of Dental Surgery	2016
High school	Al-Faisal high school	2008

Job Experience

Duty	Institution	Duration (Year - Year)
Clinical Observer	Roots dental clinics	2013
Research Assistant	Near East University	2017 - 2021

Foreign Languages	Reading comprehension	Speaking*	Writing*
English	Good	Good	Good
Turkish	Moderate	Moderate	Moderate